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## Failure Assessment Diagram in Structural Integrity Analysis of Steam Generator Tubes

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### Abstract

The assessment of the structural integrity of Steam Generator Tubes (SGTs) in nuclear power plants has been receiving increasing attention in the literature in the last years due to the negative impact related to their failures. Diverse failure prediction methodologies were proposed in the past to ensure tube integrity by fulfilling regulatory authorities' requirements. They have lead however to overly conservative plugging or repairing criteria like the so-called "40% criterion". In the present work, in line with modern approaches, an alternative more realistic methodology based on the Failure Assessment Diagram (FAD) is proposed. With that purpose, different studies available in the literature dealing with the experimental determination of fracture toughness of SGT materials were firstly reviewed. Using the results reported in these researches, the FAD was used for predicting the failure modes (i.e., ductile fracture or plastic collapse) of defective SGTs for varied crack geometries and loading conditions. The present analysis indicates the potentiality of the FAD as a comprehensive methodology for predicting the failure loads and failure modes of flawed SGTs.

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**Nomenclature**

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CTOD	Crack Tip Opening Displacement
E	elastic modulus
FAD	Failure Assessment Diagram
J	J-integral
$J_q$	fracture toughness for stable crack growth initiation
$K_I$	applied mode I stress intensity factor
$K_{mat}$	fracture toughness of a material
$K_r$	stress intensity factor ratio
$L_r$	stress ratio
PWR	Pressurized Water Reactor
SINTAP	Structural INTEgrity Assessment Procedures for European industry
SG	Steam Generator
SGT	Steam Generator Tube
TWC	Through Wall Crack
$\eta$	geometric function describing the plastic contribution to the strain energy
$\gamma$	geometric function to correct the plastic J-integral value for crack growth
$\nu$	Poisson's ratio
$\sigma$	applied stress
$\sigma_f$	flow stress
$\sigma_u$	ultimate tensile strength
$\sigma_{ys}$	yield stress

**1. Introduction**

Nuclear Steam Generators (SGs) are large heat exchangers that use the heat from the primary reactor coolant circuit to produce steam in the secondary circuit to drive turbine generators. The number of SGs per nuclear power plant can range from two to six, reaching in particular reactors up to twelve units. The SGs are shell and tube heat exchangers consisting of bundles of several thousands of tubes arranged inside a pressure vessel. The primary reactor coolant circulates through the tubes and boils the water on the secondary side to produce steam. As the primary reactor coolant is at a higher pressure than the secondary coolant, any rupture of the tubing can result in a leakage from the primary to the secondary side, leading to a potential release of radioactivity.

Also, the SGs have the function of residual heat removal from the reactor core, being their functionality an important issue concerning the plant safety during certain events or accident conditions.

Therefore, the thin walled Steam Generator Tubes (SGTs) are an essential part of the reactor, comprising up to 60% of the total primary pressure retaining boundary area. In practice, varied degradation mechanisms introduce defects which impair the structural integrity of the SGTs. These defects can be classified as in planar or crack-like (e.g., due to Stress Corrosion Cracking [SCC], fatigue and fretting fatigue) and volumetric defects (e.g., due to fretting wear). Accordingly, two failure modes that could give rise to unacceptable leak rates can occur, i.e., tube pressure bursting or crack opening. Remediation is performed by plugging the failed SGT with a consequent reduction of the overall SG efficiency. Eventually, if a sufficient number of tubes fail, the replacement of the whole SG is required. Replacement costs of SG units can range from \$100 to \$200 million dollars, Abou-Hanna et al. (2004). Therefore, it is imperative from both safety and economic standpoints to have an appropriate tool for the assessment of the integrity of flawed SGTs.

As a result, diverse regulatory requirements were developed in the past to ensure a low probability of spontaneous tube rupture under normal and accident conditions.

In this work, and following the overall trend of the nuclear power industry, a new more realistic procedure based on the Failure Assessment Diagram (FAD) is proposed for improved plugging / repairing criteria formulation. This is a comprehensive methodology involving the expected failure mechanisms of SGTs, i.e., ductile fracture and plastic collapse.

It is worth noting here that the application of a FAD type of approach requires the knowledge of mechanical and fracture properties of SGTs. Therefore, a review of the few reported experimental tests performed for fracture toughness determination of SGTs is also presented.

## 2. Structural integrity assessment methods for flawed SGTs

Traditional tube repair or plugging criteria are based on a minimum wall thickness requirement. This is because the non-destructive technique used for in service inspection, i.e., the eddy current method, gives the depth of the degradation on some particular axial location along the tube as the main result of examination. The earliest and most widely implemented guidance on this subject was published in the US Code of Federal Regulations and in the ASME Pressure Vessel and Boiler Code. The criteria established that the depth of the maximum allowable flaws shall be less than 40% of the tube wall thickness. This criterion of minimum tube thickness was initially implemented in most countries with Pressurized Water Reactors (PWR) or CANada Deuterium Uranium (CANDU) plants, IAEA-TECDOC-1668 (2011). The minimum thickness was determined as the one allowing sustaining all postulated loads with an appropriate margin of safety. For those evaluations, uniform wall thinning around the circumference of the tube was assumed. Hence, plastic limit load analyses were performed with safety margins of 3 and 1.43 against tube pressure bursting for normal and accident conditions, respectively (the so-called ASME safety factors). Usually, only the pressure difference between the primary and secondary circuits is considered in the estimation of the postulated load. Typical mechanical properties of Inconel 600 tubes were used for the analysis, as this was the principal alloy employed for SGTs at the time the criterion was proposed. Also, tube diameters of 3/4" and 7/8" were used in the assessment, IAEA-TECDOC-1577 (2007).

It is interesting to note here that, even when alternative criteria are allowed by the ASME code (subjected to previous acceptance by the regulatory authority), the 40% criterion is still worldwide used in the nuclear industry. In many cases however, the criterion is used without a clear understanding of the limitations related with the assumptions made for its formulation.

In general, a minimum wall thickness criterion works well for degradation mechanisms that results in considerable material removal (e.g., fretting wear), but can be overly conservative in case of small defects, like those originated by pitting, or crack-like defects, e.g., due to SCC, IAEA-TECDOC-1668 (2011). In order to reduce the number of tubes unnecessarily removed from service, even though they would continue to satisfy the existing regulatory guidance for adequate structural integrity, in recent years new revised fitness for service criteria were developed. Although these new criteria follow the general technical basis, there is substantial difference in their implementation. They can be roughly classified as generic criteria (e.g., the minimum wall thickness criterion, among others) or defect type / location specific criteria (i.e., different criteria for volumetric or planar crack-like defects, located in particular areas of the SGT bundle).

Among the specific criteria development for defective SGTs, some researches and contributions are available in the open literature. Due to the very high ductility of SGT materials, most of these criteria are based on limit load analysis, assuming that the plastic collapse is the prevailing failure mode, Flesch and Cochet (1990), Majumdar (1999b), Lee et al. (2001), Tonkovic et al. (2008). In fact, this is the case of the minimum wall thickness criterion of the ASME code described above. A first disadvantage of these methods is that for a particular cracked geometry and loading condition, different definitions for limit load estimation are available, Huh et al. (2006). On the other hand, the choice of a particular flow stress for the material under study has influence on the limit load estimation, Tonkovic et al. (2008). Therefore, although limit load analyses seem to be simple in practice, they need extensive supporting experimental data and still further research would be needed in order to validate their applicability.

To overcome these inconveniences, fracture mechanics based methods have been proposed to be applied to assess on the structural integrity of cracked SGTs. Some models presented in the literature consider the linear elastic fracture mechanics theory, Cizelj et al. (1995), Wang and Reinhardt (2003), Tonkovic et al. (2005), Hu et al. (2011), while other methodologies are based on the elastic-plastic fracture mechanics, Majumdar (1999a), Tonkovic et al.

(2005), Chang et al. (2006), Huh et al. (2006). These approaches can be easily generalized to different loading conditions without the need of additional experimental validation. These approaches however have a common disadvantage, i.e., the difficulties associated with the experimental characterization of the fracture toughness of SGTs, as will be showed later.

As a comprehensive option encompassing both limit load and fracture mechanics analyses, some authors proposed the use of the FAD as the most appropriate assessment technique, capable of predicting failures due to different mechanisms in SGTs, Lee et al. (2001), Wang and Reinhardt (2003), Chang et al. (2006), Tonkovic et al. (2008). Thus, at present, many structural integrity assessment procedures based on the FAD methodology have been included in the most important construction codes and guides (e.g., ASME Section XI, API 579-1/ASME FFS-1, SINTAP and BS 7910). Then, it is expected that this technique will become more familiar for most engineers in the next years.

The use of the FAD requires the tensile and fracture toughness properties of the material, being necessary to have experimental results obtained from SGTs. Reported experimental researches are reviewed in the next section. Using them, some numerical results of the FAD application to flawed SGTs will be presented in section 4.

### 3. Experimental determination of fracture toughness properties of SGTs

Concerning the degradation mechanisms affecting SGTs, a review of the open literature indicates that a significant research effort has been made on these aspects in the last decades. This has resulted in considerable improvements in the resistance to cracking problems due to corrosion or fretting phenomena. However, there are only few references devoted to the experimental determination of fracture toughness of SGTs. This may be due to the geometry and dimensions of SGTs which prevents using standardized fracture specimens in order to assure plane strain conditions. Additionally, the materials considered for SGTs fabrication possess inherent high toughness due to their austenitic microstructure. Therefore, specific alternative non standardized test techniques based on elastic-plastic fracture mechanics should be developed.

Thus, in this section a brief literature review of the J-resistance tests performed in order to determine the fracture toughness of SGTs is presented. Readers interested in more details are requested to consult the original works, Huh et al. (2006), Bergant et al. (2012) and Sanyal and Samal (2012 and 2013).

#### 3.1. J-resistance curves for Inconel 600 SGTs with circumferential cracks, Huh et al. (2006)

Huh et al. (2006) performed three J-resistance tests in Inconel 600 SGTs (chemical composition in Table 1), using specimens with circumferential Through Wall Cracks (TWCs) subjected to tensile load at room temperature. Finite element analyses were used for the determination of stress intensity factors and the geometric function  $\eta$  for the test configuration selected. The crack length was determined from the Direct Current Potential Drop method, where electromagnetic finite element analyses were used for calibrating the potential functions. Crack driving forces based on elastic-plastic fracture mechanics parameters J-integral and Crack Tip Opening Displacement (CTOD) were presented. Crack initiation and instability analyses were performed only for circumferential and longitudinal TWCs, using the lower bound values of the J-resistance tests. Table 2 presents the mechanical properties of the Inconel 600 SGTs, including the lower bound J-integral value for crack growth initiation.

Table 1. Chemical composition of Inconel 600 SGTs as reported in Huh et al. (2006).

Element	Ni	Cr	Fe	Ti	Al	Mn	Si	C	N	Co	Cu	P	S	B
%Wt	74	16	9	0.29	0.22	0.21	0.19	0.025	0.024	0.018	0.012	0.005	<0.001	<0.0005

Table 2. Mechanical properties of Inconel 600 SGTs as reported in Huh et al. (2006).

E (GPa)	$\nu$	$\sigma_{ys}$ (MPa)	$\sigma_u$ (MPa)	$J_q$ (kJ/m <sup>2</sup> )
214	0.3	259	668	471 lower bound)

### 3.2 J-resistance curves for Incoloy 800 SGTs with circumferential cracks, Bergant et al. (2012)

In a previous work, Bergant et al. (2012) presented a non-standardized experimental technique for J-resistance curves estimation. Specimens were fabricated from straight parts of SGTs, with one and two opposite circumferential TWCs, and were tested in pure tension at room temperature. The crack length growth at the external surface of the tube was followed with the aid of a digital microscope. J-integral values were assessed through the  $\eta$ -factor method. During the tests, the specimens developed generalized plastic deformation and geometric distortion. Paris et al. (1980) noticed that the occurrence of widespread plasticity during loading could invalidate the  $\eta$ -factor. In view of this, a numerical study was done in order to verify the validity of the use of the  $\eta$ -factor method. Former results showed that the  $\eta$ -factor is not valid for the tests performed, at least in a strict sense, because a certain dependence of the  $\eta$ -factor with the level of strain, load or applied J-integral was found. Averaged  $\eta$  values calculated from numerical results were therefore adopted, and J-resistance curves were estimated for circumferential TWCs for Incoloy 800 SGTs. Table 3 and Table 4 show, respectively, the chemical composition and the mechanical properties of the tubes under research.

Further numerical research showed that both bending loading configuration and the use of an alternative definition of the geometric  $\eta$ -factor which is based on the crack mouth opening displacement favor the validity of the approach.

Table 3. Chemical composition of Incoloy 800 SGTs as reported in Bergant et al. (2012).

Element	Ni	Cr	Fe	Ti	Al	Mn	Si	C	Cu	S	P	N	Co
%Wt	33.0	21.6	42.2	0.41	0.29	0.55	0.54	0.017	0.09	0.003	<0.001	0.008	<0.015

Table 4. Mechanical properties of Incoloy 800 SGTs as reported in Bergant et al. (2012).

E (GPa)	$\nu$	$\sigma_{ys}$ (MPa)	$\sigma_u$ (MPa)	$J_q$ (kJ/m <sup>2</sup> )
210	0.3	260	610	717 (lower bound)

### 3.3 J-resistance curves for Incoloy 800 SGTs with longitudinal cracks, Sanyal and Samal (2012 and 2013)

Recently, Sanyal and Samal (2012 and 2013) reported J-resistance curves for longitudinal TWCs in Incoloy 800 SGTs using the pin-loaded tension test. Table 5 presents the alloy chemical composition. In this work, finite element analyses were performed to estimate the geometric functions  $\eta$  and  $\gamma$ , and the stress intensity factors. They found that these functions are sensitive to the tube geometry, particularly with the tube diameter and wall thickness. In order to estimate the stable crack growth, J-resistance curves were obtained using the load normalization method included in the ASTM standard E 1820. Single and multiple specimen techniques were used and all the tests were performed at room temperature. The authors recommended a fracture toughness value of 250 kJ/m<sup>2</sup> for structural integrity assessments.

Table 5. Chemical composition of Incoloy 800 SGTs as reported in Sanyal and Samal (2012 and 2013).

Element	Ni	Cr	Fe	Ti	Al	Mn
%Wt	32.29	19.87	45.97	0.49	0.42	0.59

It should be mentioned that other authors have considered alternative fracture toughness values for structural integrity assessments of cracked SGTs, but the details of their determination are not available, e.g., Wilam and Cermakova (1995), Wang and Reinhardt (2003), Tonkovic et al. (2005 o 2008), Chang et al. (2006), Hu et al. (2011). In most of these cases, toughness values were inferred from fracture tests performed in similar materials but using standardized specimens obtained from other product forms, e.g., plates, obtained by different fabrication routes. This cast severe doubts about their representativeness as toughness values for SGTs.

All the previous researches required the development of non-standardized test techniques that need to be validated with more experimental work, in order to ascertain the advantages and disadvantages of each method. Also it has to be noted that all the preceding studies were performed at room temperature, whilst there are not fracture toughness properties of SGTs available in the open literature for typical operation temperatures, i.e., approximately 300°C.

It is particularly interesting the difference between the fracture toughness values reported in Bergant et al. (2012) and in Sanyal and Samal (2012 and 2013). Although both studies were carried on with similar material (i.e., annealed Incoloy 800 with almost equal tube geometry), very dissimilar values of fracture toughness were measured for longitudinal and circumferential cracks. This can be attributed to the anisotropy of the material, being necessary the distinction in the type of crack for structural assessments.

Therefore, if more accurate structural integrity predictions are required, it is indispensable more experimental research dealing with fracture toughness determination for actual SGTs, exploring different aspects as the particular alloy used (e.g., Incoloy 800 or Inconel 600 and 690), type of crack (e.g., circumferential or longitudinal) and actual temperature of operation.

#### 4. Structural integrity analyses using the FAD

##### 4.1. The FAD methodology

Once the mechanical and fracture toughness properties of SGTs are experimentally determined, the next step consists in the structural integrity assessment of tubes with crack-like defects under different loading conditions. This type of analysis can then be used to define the plugging / repairing criteria and inspection strategies for nuclear SGs.

As mentioned earlier, due to the austenitic microstructure of the SGT materials, very high fracture toughness values were measured. Then, the failure mechanism is expected to lie between ductile fracture and plastic collapse of the remnant ligament. In the literature dealing with structural integrity assessments of SGTs it is possible to find analyses based on plastic collapse and limit load, as well as methodologies of elastic-plastic fracture mechanics and even of linear elastic fracture mechanics.

One way to analyze this problem is evaluating the integrity in terms of the FAD, known as criterion CEGB R6 or simply R6. It is a two criteria approach that considers the linear elastic fracture mechanics and the plastic collapse as two extreme forms of cracked component failure, while for elastic-plastic material, the failure will occur in an intermediate state.

This method requires the definition of two parameters, one based on a fracture mechanics and the other in plastic collapse criteria. These parameters define the coordinates of an assessment point in the FAD, whose position relative to the failure line determines the safety degree of the component. Then, in order to assess the significance of a particular flaw in a component, the driving forces in terms of toughness and stress ratios are determined respectively as:

$$K_r = \frac{\text{applied stress intensity factor}}{\text{material's fracture toughness}} = \frac{K_I(a, \sigma)}{K_{mat}} \quad (1)$$

$$L_r = \frac{\text{reference stress}}{\text{yield stress}} = \frac{\sigma_{ref}}{\sigma_{ys}} \quad (2),$$

where the reference stress  $\sigma_{ref}$  is traditionally based on limit load solutions for the configuration of interest.

The FAD provides a failure line, above which predicts the failure of the structure. All points inside of the FAD are considered safe, whereas points outside of the diagram are unsafe. The final step in creating the FAD is introducing a cut-off value  $L_{r\ max}$  on the horizontal axis, which represents a limit load criterion. Thus, the FAD is an analysis tool for assessing structural integrity of components that can fail in several ways. In the particular case of

cracked SGTs, the FAD can predict whether the failure is due to stable crack growth (or even ductile instability) or because of plastic collapse.

#### 4.2. Structural integrity assessment of SGTs using the FAD

In this chapter, structural integrity assessment results of flawed SGTs based on the FAD are presented. Circumferential and longitudinal crack-like defects were modeled, and a typical SGT geometry was adopted, i.e., 15.88 mm and 1.13 mm for outside diameter and wall thickness, respectively. The loading conditions considered were the pressure difference between primary and secondary circuits for longitudinal flaws and tensile loading for circumferential cracks. Actual tensile and fracture toughness properties of SGTs were used and are summarized in Table 6.

Table 6. Summary of mechanical properties at room temperature of SGTs used for structural integrity assessments.

Reference	SGT material	$\sigma_{ys}$ (MPa)	$\sigma_u$ (MPa)	$\sigma_f$ (MPa) $1.15(\sigma_{ys} + \sigma_u)/2$	Crack orientation	$J_q$ (kJ/m <sup>2</sup> ) (lower bound)	$K_{mat}$ (MPa.m <sup>0.5</sup> ) (lower bound)
Huh et al., 2006	Inconel 600	259	668	533	Circumferential	471	317
Sanyal and Samal, 2012	Incoloy 800	260 <sup>(*)</sup>	610 <sup>(*)</sup>	500	Longitudinal	250	222
Bergant et al., 2012	Incoloy 800	260	610	500	Circumferential	717	375

<sup>(\*)</sup> This values are not reported in Sanyal and Samal (2012 and 2013), but are assumed equal to the values measured in Bergant et al. (2012) since the material is similar.

In order to estimate the driving forces for different geometries, the structural integrity evaluations were performed following the API 579-1/ASME FFS-1 procedure. For the FAD shape, the simplest option was adopted, i.e., the Level 2 assessment proposal which is a generic shape independent of the material and the component geometry. The flow stress  $\sigma_f$  was estimated as  $1.15(\sigma_{ys} + \sigma_u)/2$ , which is the value recommended for austenitic materials in the API 579-1/ASME FFS-1 guide. The cut-off value  $L_{r\max}$  was calculated as  $\sigma_f/\sigma_{ys}$ , i.e., approximately 2 for all cases. The stable crack growth initiation was adopted as the failure condition for fracture. Therefore, fracture toughness values for crack growth initiation were used in Equation 1, and were obtained from the values of  $J_q$  reported in Table 6 through the equivalence between K and J, Anderson (2005).

Although the crack growth initiation criterion can be adequate to prevent part through cracks to produce leak (i.e., to become TWCs taking into account the typical thin walls of SGTs), it can be conservative for predicting unstable crack growth.

#### 4.3. Failure mode prediction using the FAD

Fig. 1 shows the FAD for circumferential cracks in a tube under tensile load (a), and longitudinal cracks in tubes under internal pressure (b). Both semi-elliptical and through wall cracks were considered. For a given crack geometry, when the load or pressure is increased the assessment points move following a line, called the loading line. The slope of this loading line is defined by the cracked component geometry and the type of loading. The intersection of the loading line and the failure line of the FAD determines the condition (i.e., the load level) for the component failure.

It can be seen that for circumferential cracks the failure mode predicted by the FAD is closer to plastic collapse. This is particularly evident for semi-elliptical or short cracks. On the other hand, for relative large longitudinal cracks the failure mechanism falls in the region dominated by fracture and plastic collapse. It must be noted that in the last case, a solely plastic collapse analysis will give a non-conservative prediction of the failure.

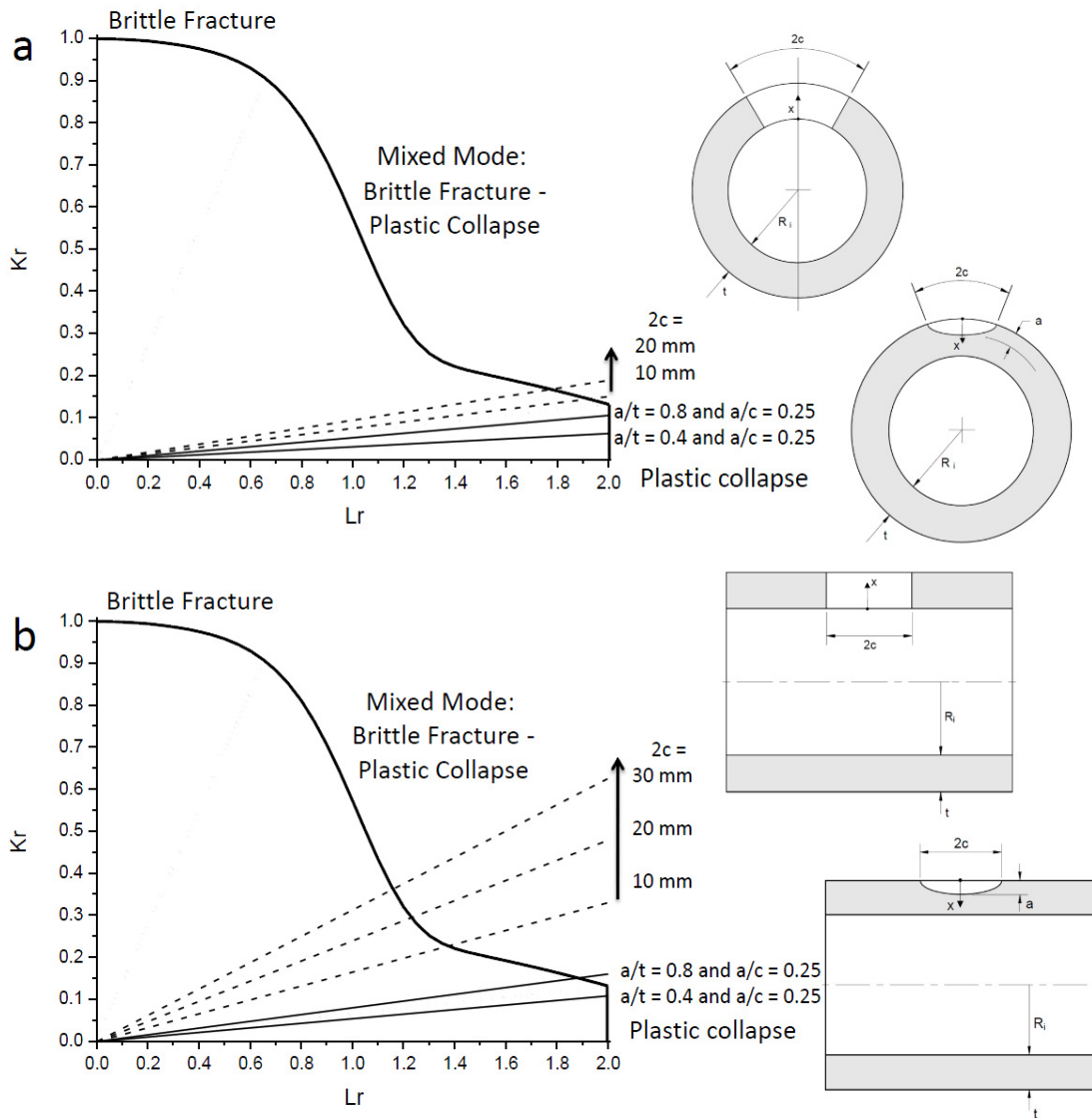


Fig. 1. FAD assessments for (a) circumferential cracks in a tube loaded in tension and  $J_q = 717\text{ kJ/m}^2$  (Bergant et al., 2012); (b) longitudinal cracks in a tube under internal pressure and  $J_q = 250\text{ kJ/m}^2$  (Sanyal and Samal, 2012 and 2013).

#### 4.4. Conservatism of traditional plugging / repairing criteria

As already mentioned, the traditional minimum wall plugging / repairing criteria for SGTs has been demonstrated to be excessively conservative. The degree of conservatism can be appreciated using the FAD methodology. The same basic hypothesis behind the minimum wall criterion in the ASME code (i.e., flaws shall be less than 40% of the wall thickness) were used in order to get comparable results. Therefore, a cracked tube will be analyzed with the differential pressure as unique loading condition, affected by the ASME safety factors. Under normal operating conditions, the pressure across a typical PWR SGT wall,  $\Delta P_{NO}$ , is about 9 MPa. Under accident conditions (i.e., due to steamline break in which the secondary side has dropped to atmospheric pressure), the differential pressure  $\Delta P_{ACC}$  can reach 18 MPa. Therefore, the defective tubes must actually be capable of withstanding  $3x\Delta P_{NO}$  and  $1.43x\Delta P_{ACC}$



(i.e., 27 and 26 MPa, respectively) for continued operation, Majumdar (1999b). For the crack geometry an internal infinite part-through crack was adopted, 40% of tube wall depth. Considering the worst condition, the crack is located longitudinally and a fracture toughness of  $250 \text{ kJ/m}^2$  was used. Fig. 2 shows the FAD results for the conditions mentioned. The point assessment corresponding to a crack depth of 40% of the tube wall thickness falls behind the failure line, being a safe condition. Actually, the FAD methodology predicts the failure by plastic collapse when the crack depth reaches 63% of the tube wall thickness. This result shows the conservatism of the ASME code criterion even in limiting cases. The same analysis applied to a circumferential crack (with half membrane stress due to the differential pressure and higher toughness) or to a longitudinal crack with non-infinite length would give higher tolerable depths.

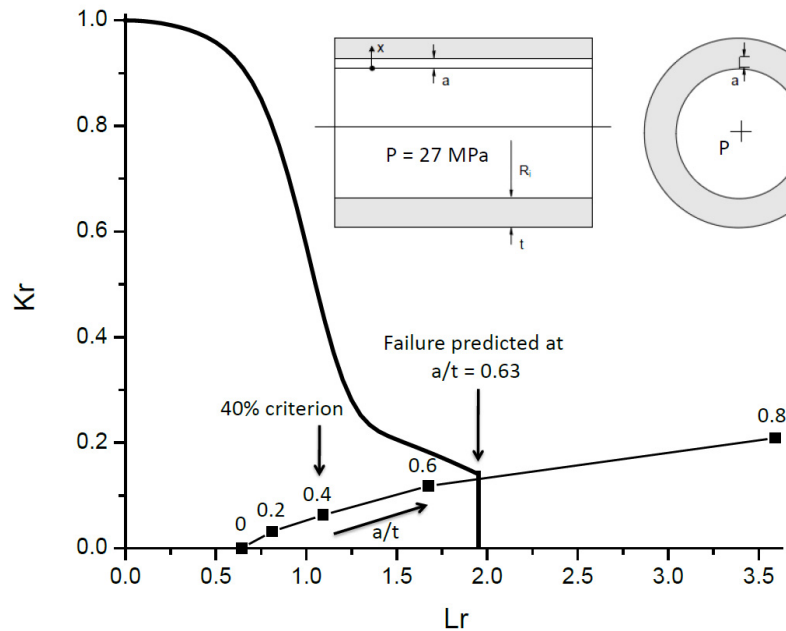


Fig. 2. Comparison between the 40% criterion and the FAD methodology.

## 5. Discussion

The previous results show the convenience in the use of the FAD methodology for structural integrity assessments of SGTs, due to its ability of predicting different failure modes.

Recalling Fig. 1, the FAD analysis can predict the expected failure modes for cracked SGTs, enabling the selection and use of an adequate assessment methodology (e.g., elastic-plastic fracture mechanics for stable crack growth initiation and ductile instability, or limit load for plastic collapse). As mentioned before, a non-conservative assessment can be performed if only the traditional plastic collapse analysis is applied to through-wall longitudinal cracks. This mistake can be easily avoided with a FAD methodology.

The analysis performed in Fig. 2 shows the evident capability of the FAD procedure to reduce the unnecessary conservatism in structural integrity assessments, even in limiting cases (the same is applicable to other detailed analysis taking into account the flaw location and actual properties of SGTs). Actual cracks in SGTs can be located and sized more precisely nowadays, so the use of sophisticated assessments becomes attractive.

Another advantage regarding the FAD methodology is their widespread use in different industries, through fitness-for-service guides as API 579-1/ASME FFS-1 or the XIth Section of the ASME code. Also due to their easiness, the FAD assessments are becoming more familiar for engineers and structural professionals, while the technique is becoming more reliable.

Perhaps the most limiting condition for accurate structural integrity assessments of defective SGTs with the FAD methodology lies in the lack of experimental results and convincing testing techniques for fracture toughness determination. Besides the few experimental data in literature, the testing techniques reported present some difficulties that must be resolved so then can be reliable, Bergant et al. (2012). These techniques should include fracture toughness resistance curves tests for circumferential and longitudinal cracks in actual SGTs, particularly in terms of elastic-plastic fracture mechanics parameters as the J-integral or CTOD. Also high temperature tests are needed to assess flawed SGTs at operation conditions.

## 6. Conclusions

A brief introduction to the structural integrity assessment methodologies used for flawed SGTs was presented. These methodologies are based mainly in plastic collapse analyses and, in minor extent, on linear elastic and elastic-plastic fracture mechanics. The FAD methodology is then proposed as a comprehensive option. In order to apply the FAD procedure, tensile and fracture toughness data of actual SGTs are required. A summary of fracture toughness tests in SGTs reported in open literature is offered. Using this experimental data, structural integrity evaluations were performed following the FAD procedure according to the Level 2 Assessment of the API 579-1/ASME FFS-1 guide. It was shown that the FAD can predict different failures modes (i.e., ductile fracture and plastic collapse) for different crack geometries, crack locations and loading conditions. Also, traditional plugging criteria in the ASME code was evaluated and compared with a FAD prediction, evidencing the degree of conservatism of the former and the potentiality of the FAD methodology in order to get more accurate integrity assessments for cracked SGTs.

The reduction of excessive conservatism in the plugging criteria through the FAD methodology requires, on the other hand, further experimental research for fracture toughness estimation in SGTs. Testing should include specimens with circumferential and longitudinal cracks at typical SG operation temperatures.

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